Store separation simulation studies in high-speed wind tunnels

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The various methods used for store separation trajectory are discussed in brief, along with their relative merits and demerits. The most captive trajectory technique, commonly used in high-speed wind tunnels is described in some detail. A few examples of the trajectories obtained in the NAL 1.2 m wind tunnel using the CTS rig are discussed.

Nomenclature

I	Moment of Inertia
L	Length
M	Mach number
N	Scaling Factor
t	Time
V	Velocity
W	Weight
Z	Vertical distance
ρ	Density of air
θ	Pitching angle
ψ	Yawing angle
α	Angle of incidence

Subscript

m	Model
f	Full scale
∞	Free stream
0	Initial condition

Introduction

The word 'store' is generally defined as any object (bomb, weapon, rocket, fuel tank, etc.) which is carried on an aircraft. Thus, store separation studies are concerned with the simulation and determination of the position and attitude histories of a store after it is separated or ejected from the aircraft, but is still in the complex and non-uniform flow field of the parent aircraft.

The aerodynamic problem of releasing the store from the parent aircraft needs individual attention to ensure safe, acceptable separation and minimum deviation from the intended flight path. The flow field of an aircraft store combination is complex and non-uniform having large variations in down wash, side wash and local dynamic pressure along both longitudinal and lateral directions (Figure 1). In addition to these, the flow field also gets modified because of the presence of the stores and their support devices. Because of these, large changes in the flow field parameters and corresponding changes in the store loads and moments are also encountered. As a result of these, the store will exhibit in most of the cases erratic separation characteristics after release or ejection.

The problem can be more severe at transonic and supersonic speeds because of the presence of shock waves and their interaction on the store flow field. Hence, unless a careful study of the problem is made, it can result in reduction in the allowable delivery speed of the store, increased dispersion and even in rare cases loss of the parent aircraf. Therefore, store separation problem is very important in determining the safe/effective separation of any aircraft delivered object.

a

b

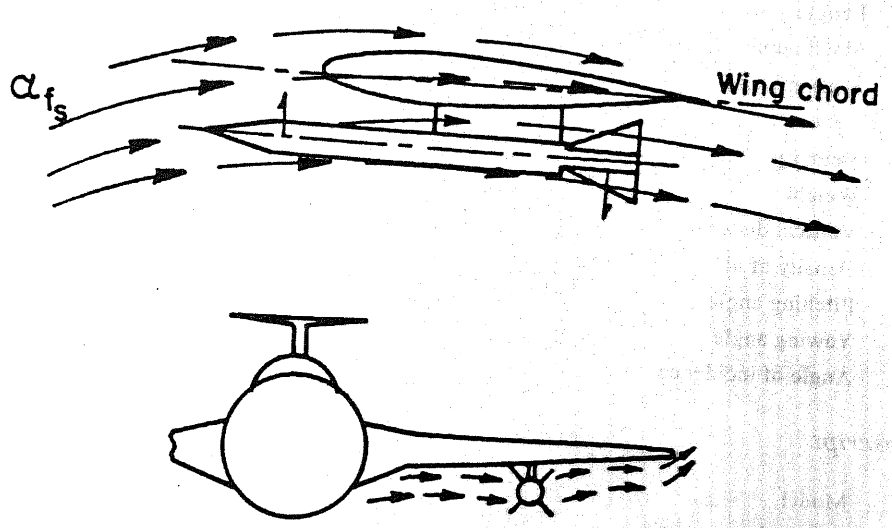


Figure 1. **(a)** Induced flow field in pitch, due to wing–pylon–store combination; **(b)** Induced flow field due to cross flow.

Wind tunnel simulation of store separation trajectory has assumed great importance in recent times when different types of stores are being integrated with different aircrafts. Often, the weapon designer, in addition to ensuring the required ballistics for the store, is also concerned about the safe separation of the store when released from the parent aircraft under critical flight conditions. Though available theoretical methods predict reasonably accurate trajectories at moderately high speeds, experimental techniques are inevitable when the flight Mach number is transonic and also release at high load factors.

Several techniques (both theoretical and experimental) are in use to simulate the conditions of separation. A review of these techniques and their relative merits and demerits together with a bibliography are given in Reference 1. A detailed description of a technique (captive trajectory) which has been extensively used successfully in high-speed wind tunnels is given in Reference 2 along with some test examples. The material covered in this paper is drawn mainly from these two references.

Techniques for generating store separation data

Attitude and time history of the store after release or ejection from the parent aircraft in the vicinity of a complex flow field can be generated experimentally and theoretically. These techniques are described briefly in this section.

Experimental techniques

Generally a wind tunnel is used for generating store separation characteristics. There are several techniques in use and they are given below.

Scaled dynamic separation method. Separation studies are made by releasing or ejecting dynamically similar scaled model of the store in a wind tunnel and following the model free flight by photographic means. High-speed motion cameras are used to record its trajectory just after separation from the aircraft. Cameras are located as so to take snaps from the side and the bottom. The model is illuminated by stroboscopic light. Each frame may be analysed and trajectory data obtained. The model is recovered generally by putting a net downstream of the test section in the case of a low-speed wind tunnel test; on the other hand, the model generally gets destroyed in a high-speed wind tunnel test.

The static forces and moments generated by the flow field will be scaled if the flow field and model geometry are similar to those of the full scale. Aerodynamic acceleration will be similar if the static forces, moments, mass, e.g. and mass moment of inertia are scaled. The inability to scale gravity acceleration in this method of scaled dynamic separation results in erroneous separation characteristics. This gravity simulation problem could be solved by giving an additional ejection force to the model as it separates from the aircraft. The important parameter is the momentum and not the velocity, which should be simulated at the time of separation.

Grid method. The grid method or flow field survey method is used when a large number of store separation trajectories are required. In this technique the models of both the parent aircraft and the store are mounted independently in the wind tunnel. The store is mounted on a strain gauge balance and the forces and moments on the same are measured at different grid points covering spanwise, chordwise and vertical directions in the vicinity of the complex flow field. Once the data bank is obtained and initial conditions are defined, a computer is used, off-line, to calculate the store trajectory using the data bank of interference force and moment coefficients. A number of trajectories can be obtained by changing the initial conditions. In this method a generalized store cannot be used since the flow field is generated not by the parent aircraft alone but by a combination of both. This makes it necessary to use a particular store and parent aircraft in the study.

Point prediction method. The separation characteristics could be determined if initial aerodynamic forces and moments on the store are known from the wind tunnel along with the appropriate equations of motion. This is accomplished by predicting the attitude and relative position of the airplane and store at successive small intervals of time. At each incremental time aerodynamic data are obtained (experimentally or theoretically) and are used to predict the characteristics for the next time interval. This process is started from the time of store release and is continued as long as desired. Basically, this method is similar to the grid method but the main difference between the two lies in the manner in which the aerodynamic data are obtained. In the grid method, the force and moment coefficients are interpolated from the grid data during each cycle (time increment). On the other hand, in the point prediction method the values of aerodynamic coefficients are obtained either from direct wind tunnel measurements or calculated theoretically by extrapolating the interference over a time interval.

Captive trajectory method. Early captive trajectory tests investigating store separation characteristics were limited in their objectives due to lack of experience in the technique and instruments. The first few test were made in mid-fifties using crude hardware at the Cornell Aeronautical Laboratory, David Taylor Model Base (DTMB). In the late fifties similar trajectory tests were made at Vought Aeronautics (USA) with modest investments. In these tests servo-controlled devices were used to make the system automatic, but this was limited to single degree of freedom. In the early sixties, a modified and most sophisticated technique, now being extensively used in most of the wind tunnels for store separation, was developed at DTMB.

This technique[2–4] utilises a six-degree-of-freedom, closed-loop servo-controlled sting support mechanism in conjunction with a computer, which is called the captive trajectory rig, to simulate the store trajectory. The parent model and store model are mounted independently in the wind tunnel. The store model is mounted on the sting of captive trajectory rig sting and positioned against the aircraft model in its 'carriage' position. An internal strain gauge balance senses the loads on the store. These balance loads are fed to the computer, which solves the equations of motion of the store (under full-scale conditions) on-line and predicts store motion parameters at known intervals of time.

These parameters are converted to control signals, which in turn are used to actuate the servo-valves and electric motors. The store is thus actuated to follow the computer-determined path. The difficulties generally faced in other techniques, i.e., gravity vector scaling, ejection force, etc., can be avoided by this method. A detailed description of this rig and accessories (The NAL Captive Trajectory System (CTS) is given later.

Full-scale flight drop test technique

In this method the full-scale store is dropped during actual flight of the parent aircraft. The trajectory of the store is recorded on the ground by telemetry. Another method of recording the path is by use of high-speed movie camera. Cameras are fixed to the parent aircraft. In addition, ground-based radars track the drop aircraft, prior to release, and thus define the initial conditions at release. From telemetry the position and the attitude history of the store could be recorded in the form of graphs and analysed. If the trajectory is recorded on a high-speed movie film, it can be analysed frame by frame, though it is very time-consuming. A better method, called photo data analysis system (PDAS), has been developed[5] to analyse the film having superpositions of two images. One of these images is from a movie film taken during the free-flight drop and the other is the image of the scaled model of the store positioned in such a way as to produce an image of the proper size and orientation for perfect superpositions. The images are obtained by video cameras and superimposed by video mixing. When the two images coincide, the position and the attitude data are recorded relative to the parent aircraft. This method is more accurate and faster than the conventional method.

Theoretical technique

In general, final store separation studies are based on extensive and expensive wind tunnel tests or full-scale flight drop tests. Over the years, the importance of theoretical generation of store separation characteristics was felt during the preliminary design phase. This analytical technique saves time and money in the initial stages of design and development of the store. Computer programs have been developed at a few places to compute the theoretical separation trajectory of an external store released from the aircraft, flying at subsonic speeds[6–10]. These computer programs take into account the effects of fuselage, separated store body and any other store carried by modelling them using point source and sink distribution along the centreline of the body. The aircraft wing and wing pylons are modelled by using vortex lattice method which includes any dihedral, camber and twist of the aircraft wing. Thickness strips are used to model the thickness of the aircraft wing and pylons.

The computer program first calculates the forces and moments acting on the store in its normal carriage position within the nonuniform flow field. Then it uses six-degree-of-freedom trajectory calculations to compute the motion of the store for a small time interval. The forces and moments acting on the store are computed again for the new position and the procedure is repeated until the separated store has traversed the non-uniform flow field near the aircraft.

The theoretical store separation problem does not end with the computation of the separation trajectory but is also required to present the results in a concise manner. Two of the methods which are in general use are given here: (i) interactive computer graphic method, and (ii) visual documentation computer method.

In the first, the interactive graphic method,[7–8] the separation is displayed visually on the screen showing two views, plan and side views, which give the immediate information on the store trajectory. After the run is complete the store coordinates can be plotted relative to the parent aircraft and it can be judged whether the separation is acceptable or not. With the instantaneous results of graphics, the user can make changes to the input, based on the display and rerun the trajectory until satisfactory results are obtained. In this method it is possible to define values of variables at will during the run from the graphics console.

The second method provides permanent visual documentation in the form of a movie, slides, etc. This system[9] uses a computer program to generate a magnetic tape of command signals for an off-line plotter. This off-line plotter is used to prepare pictures, slides or movies. More details of this method are given in Reference 10.

Scaling parameters of dynamic separation

In dynamically scaled store separation, it is necessary to assume that flow field around the aircraft is scaled and the forces experienced by the store model are directly scaleable to full-scale flight. Also, in addition to this, weight and moment of inertia of the store must be properly scaled. Generally, three methods are used for dynamically scaled separation studies: (a) light scaling, (b) Froude scaling, and (c) heavy scaling.

Light scaling

In light scaling two parameters are considered to be important, Mach number (M) and the ratio of store density to air density ($m/\rho l$). This implies that full-scale performance of the store may be simulated in the wind tunnel by satisfying the following relations:

$L_m = (1/N)L_f$ (Length)

$M_m = M_f$ (Mach number)

$(W/\rho)_m = (1/N^3)(W/\rho)_f$ (Density)

$(I/\rho)_m = (1/N^5)(I/\rho)_f$ (Moment of inertia)

Froude scaling

In Froude scaling the ratio of inertia and gravitational forces and the store to air density ratio are simulated. In other words, the following relationship should be simulated:

$V_m = (1/N^{1/2})V_f$ (Velocity)

$(W/\rho)_m = (1/N^3)(W/\rho)_f$ (Density)

$(I/\rho)_m = (1/N^5)(I/\rho)_f$ (Moment of inertia)

Heavy scaling

In heavy scaling free-stream Mach number and the ratio of static aerodynamic forces to gravity forces are the scaling parameters. It is assumed here that the scaled trajectory will be obtained in the normal gravitational field if the pitch oscillations at release are small. In other words, the time for which the store is very close to the parent aircraft is generally small compared to the period of the longitudinal oscillations.

This method of scaling gives the following relations:

$M_m = M_f$ (Mach number)

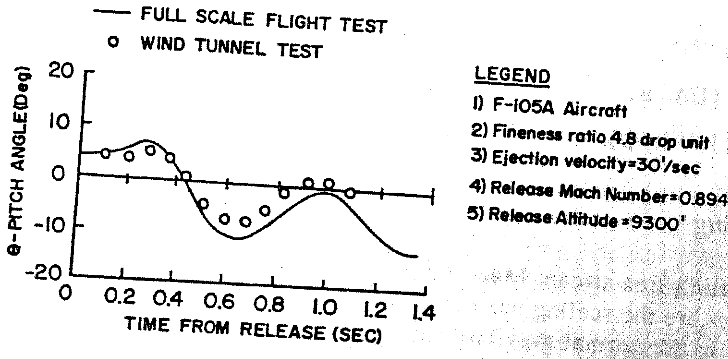
$(W/\rho)_m = (1/N^2)(W/\rho)_f$ (Density)

$(I/\rho)_m = (1/N^4)(I/\rho)_f$ (Moment of inertia)

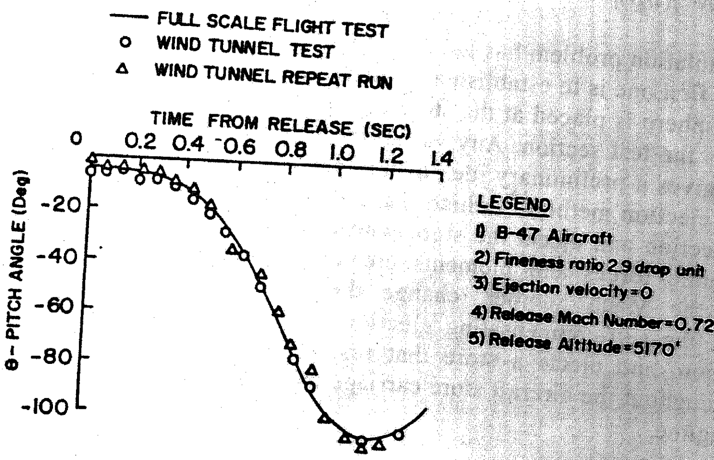
The gravity simulation problem has led to further investigation and two other methods are suggested. The first one is to establish a magnetic field on either side of the test section. A ferromagnetic sphere is placed at the store e.g. and a field of constant flux distribution is imposed across the test section. Any variation in field strength can simulate the gravity. Reference 11 gives a preliminary idea of this method. The second one is known as self-compensating ejection method[12], which takes into account the aircraft flight condition at the time of ejection and ejects the store with an initial angular rate and linear velocity. The aerodynamic forces and moments created by nonuniform flow field, which are functions of the Mach number, change the initial launch condition of the store. Conceptually, the self-compensating ejection method takes care of this change in the initial condition, and ejects a store that results in a safe, repeatable and predictable trajectory throughout the aircraft store carriage envelope. This concept is important in the supersonic regime.

Limitations of the various techniques

The techniques used for generating the store separation characteristics have their own limitations, advantages and disadvantages. In this section some of the limitations, relative advantages and disadvantages are given. The main problem in the dynamically scaled



(a) LIGHT SCALING METHOD



(b) HEAVY SCALING METHOD

Figure 2. Comparison of wind tunnel results with full-scale drop tests.

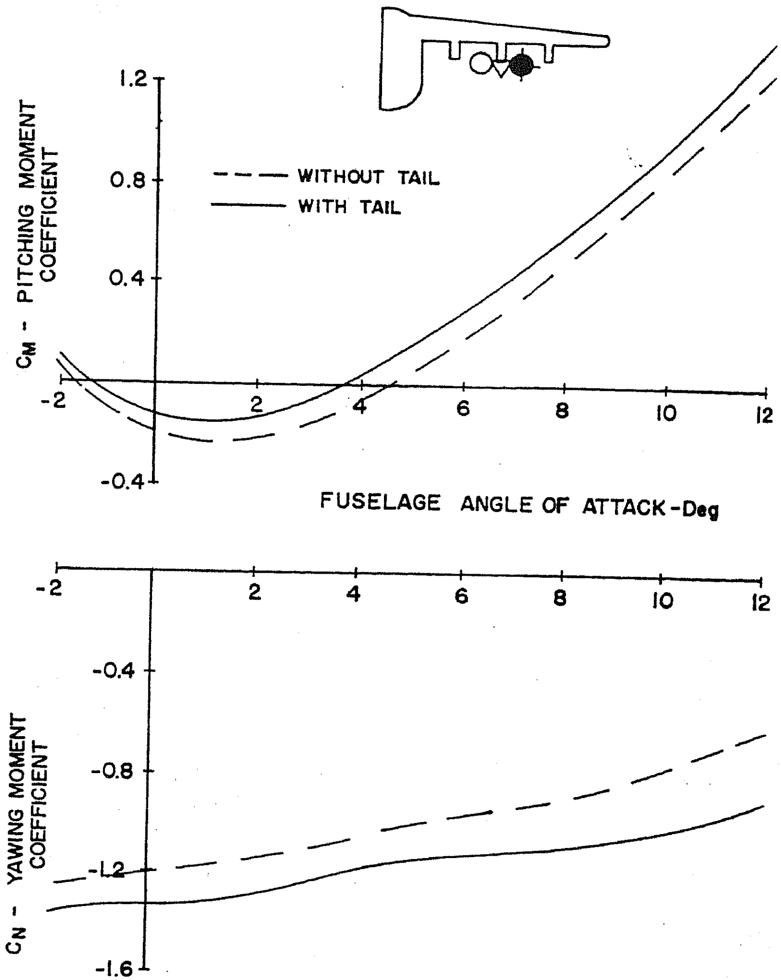


Figure 3. Effect of aircraft horizontal tail on capture store model.

separation method is the simulation of the gravity acceleration. Both the methods of light and Froude scaling produce correct dynamic response of the store model to aerodynamic loadings, but, since the store gravity acceleration is not sealed, the store does not pass through a proper flow field. Heavy scaling, where the Mach number is held constant, produces underdamped response of the store model to aerodynamic acceleration. Figure 2 shows a comparison of light and heavy scaling with flight data and confirms the better agreement of heavy scaling with the flight data. In light scaling, the unscaled gravity acceleration may be compensated by giving an initial momentum to the separating store. This initial momentum given to the store can approximate the velocities that would be obtained if gravity were scaled, for the early portion of the trajectory. This gravity scaling problem can be solved further by either creating the scaled gravity field across the test section or by ejecting the model from the self-compensating ejection rig.

In captive trajectory simulation, an assumption is generally made that the flow field of the parent aircraft is duplicated in wind tunnel as in free flight. But flow field disturbances, if any, resulting from store acceleration are not simulated because in the wind tunnel it is physically impossible to duplicate a velocity difference that exists between the parent aircraft and the store. Also, disturbances such as the parent aircraft wing deflection resulting from the store launch cannot be simulated. Captive trajectory testing is generally done without horizontal tail to avoid any physical interference with the store support sting. Though not obvious, significant effect of tail surface has been observed[13] on the store forces and moments. Figure 3 shows this effect at $M = 0.9$. Captive trajectory method provides an on-line method of simulating store trajectory and is recommended only after the store design is reasonably well defined since it is very expensive.

In the following section the captive trajectory system which has been in use in the 1.2 m tunnel of NAL since a couple of years, together with some results, is described briefly.

The captive trajectory system of NAL 1.2 m wind tunnel

NAL had been using a simpler technique called the semi-captive trajectory technique[14] for store trajectory simulation for nearly a decade. The technique, though accurate, was laborious and about 15 runs were required for obtaining a single trajectory. However, with the financial support from the Aeronautical Development Agency, Bangalore, a fully automatic captive trajectory system (CTS) was acquired and commissioned in 1990 at the 1.2 m tunnel of NAL. This system was designed and built by Nutem Ltd., England, as a turnkey project to NAL's specifications.

Main features of the CTS

The following are the important performance features of the CTS:

March number range	0.4 to 1.8
Number of data points	20–25 in 30 s

Maximum drive speed

Axial	100 mm/s
Primary	18.0°/s
Secondary	18.0°/s
Roll	18.0°/s
Pitch	4.0°/s
Yaw	5.8°/s

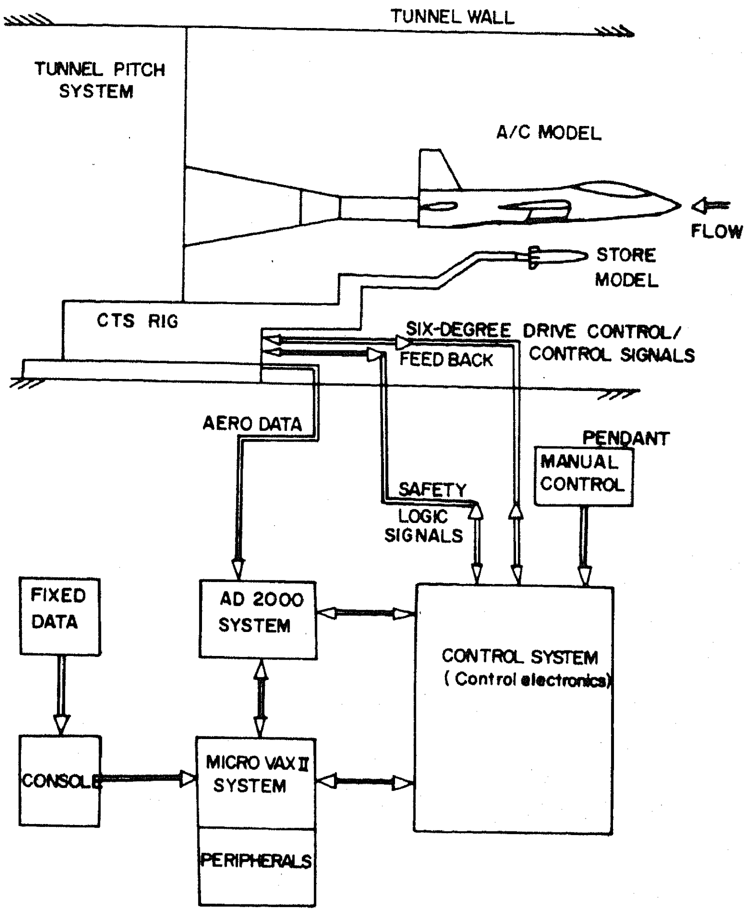


Figure 4. Schematics of captive trajectory system.

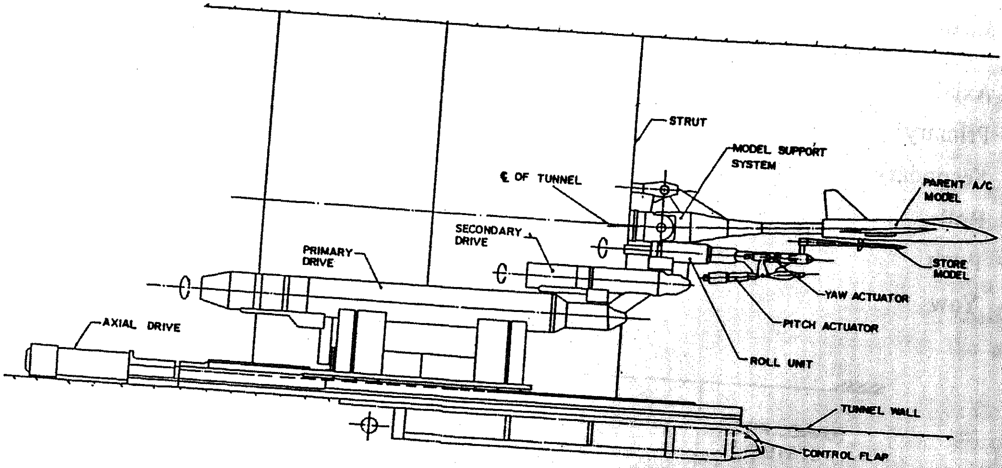


Figure 5. Outline of the NAL CTS rig.

Range of movement

Axial	800 mm
Lateral	450 mm
Vertical	450 mm
Roll	± 90°
Pitch	± 25°
Yaw	± 45°

Store positioning accuracy

Linear	± 0.5 mm
Angular	± 0.1°

The complete details, viz. mechanical system, control system, computer hardware and software, data acquisition system, calibration of the NAL CTS, etc., are given in Reference 2. The functioning of the CTS is schematically shown in Figure 4. An outline of the CTS rig is given in Figure 5 and the CTS integration algorithm in Figure 6.

Commissioning tests

The commissioning of the CTS was successfully completed in November 1990 a[illegible] critical assessment of the rig through bench tests and wind-on tests.

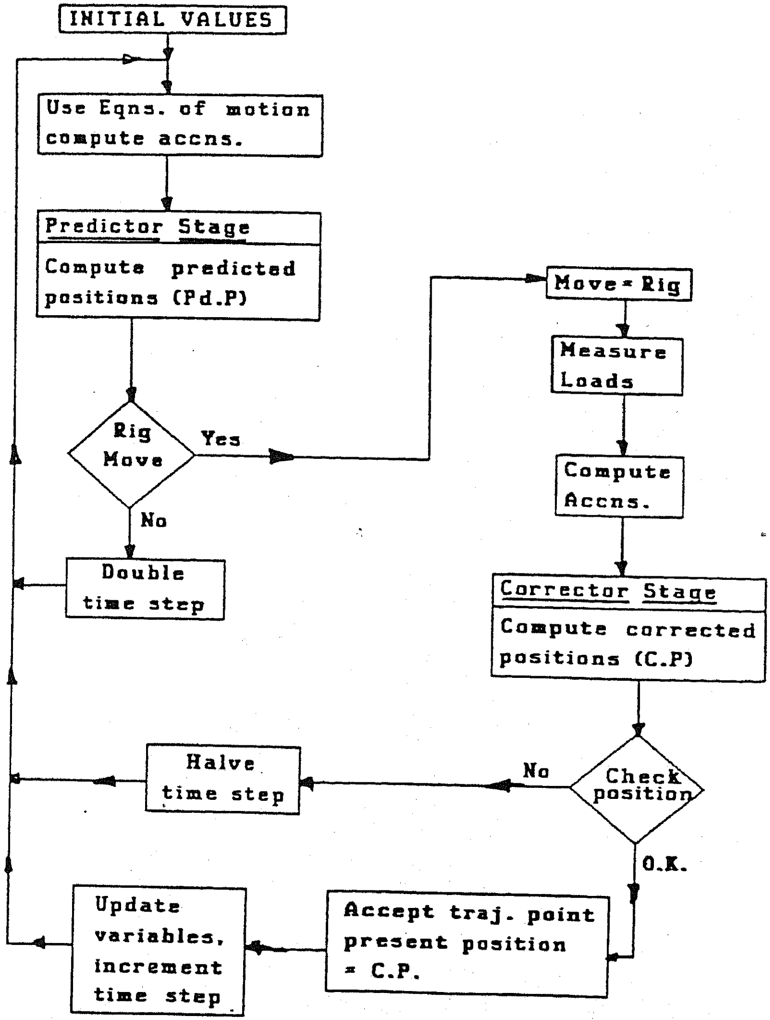


Figure 6. CTS integration algorithm.

Bench tests

With the CTS mounted on trolley outside the tunnel, all the six drives were checked for positional accuracies and drive speeds. The balance output and deflections were monitored for several loadings. The system safety features and logic checks were done by simulating several failure or error conditions. The total compatibility of the system was

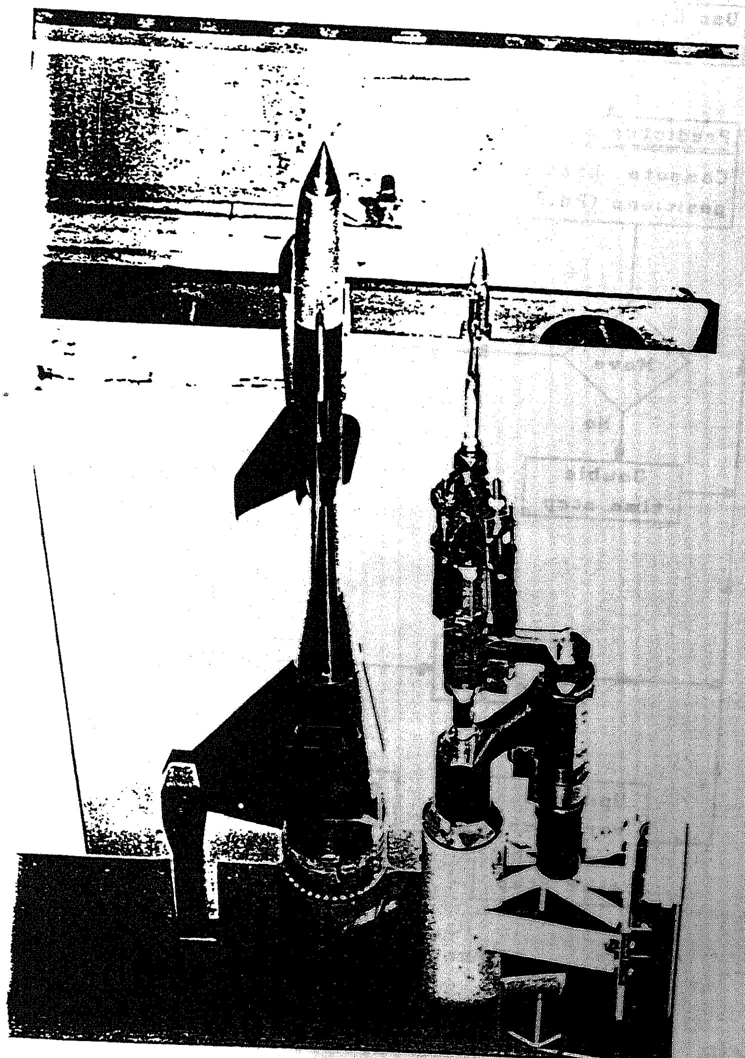


Figure 7. Photograph of the CTS rig mounted in the tunnel

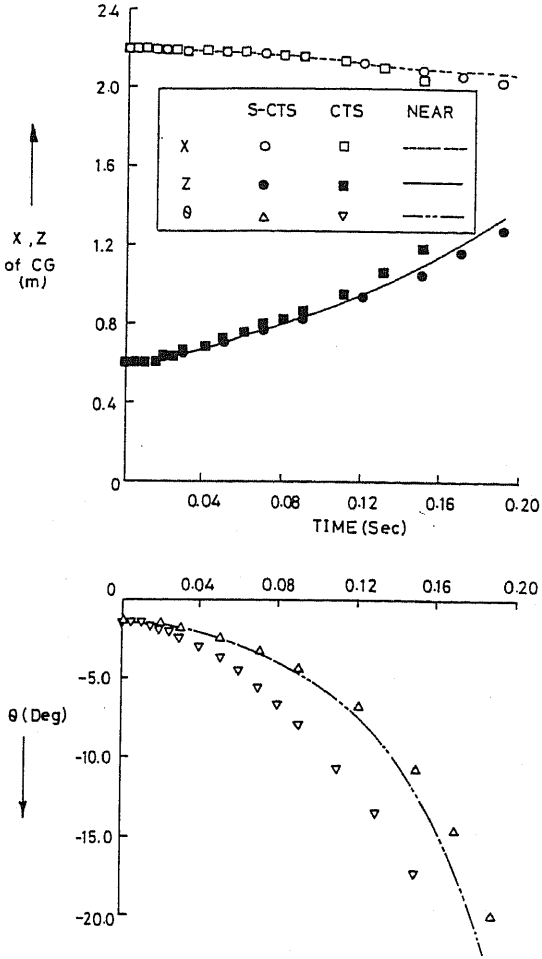


Figure 8. Comparison of CYS trajectory of Store 1 with results of S-CTS and NEAR methods (Mach number M = 0.75, aircraft incidence = 1.6°).

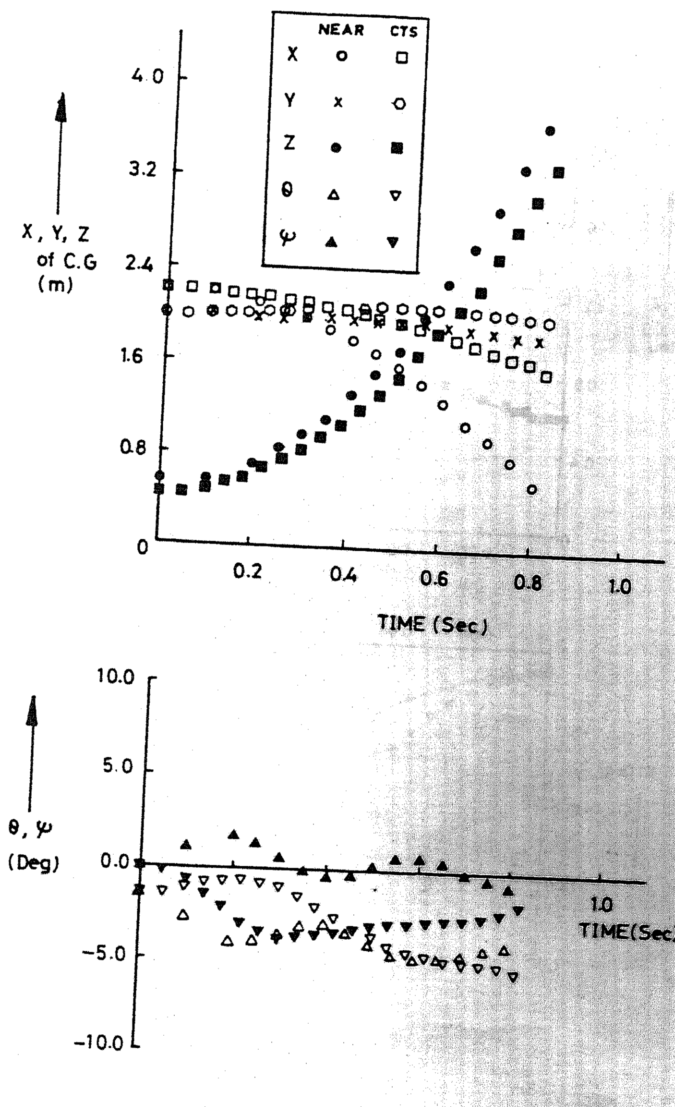


Figure 9. Comparison of the trajectory results of Store 2 with the results obtained from the NEAR m
(Mach number $M = 0.7$ and aircraft incidence = 2.53°).

tested by repeating several grid modes within the control volume. Tests were repeated in coefficients simulation mode with assumed aerodynamic coefficients of the store as input.

Wind-on tests

After assuring the satisfactory performance of the CTS on the trolley, wind-on tests were carried out on the CTS after integrating it with the tunnel circuit logics. Tests were carried out both in grid and trajectory modes. Figure 7 shows the photograph of CTS mounted in the tunnel test section. To check the effectiveness of safety features of the CTS under real-life conditions, several 'unsafe' conditions were intentionally created in some of the wind-on runs. The safety features of the system were found to be effective in all the cases. In addition, collision of the store model with the parent aircraft model and the sting, which occurred unintentionally during a few of the runs proved satisfactorily a proper functioning of the safety interlocks without causing any damage to the model and the sting.

CTS trajectory

Trajectories of three store models released from a particular aircraft were obtained covering a Mach number range up to 1.6. Figure 8 shows a typical release trajectory of an unstable store (Store 1) at a Mach number of 0.75 and aircraft incidence 1.6°. The entire trajectory was obtained in a short blowdown because of the occurrence of near collision of the rig with the sting. This trajectory is compared with the trajectories obtained earlier using semi-captive trajectory technique (S-CTS) and the results using AFFDL NEAR method are reported in Reference 5. The comparison is fairly good for the longitudinal characteristics. The slight disagreement observed in pitch angle could be due to small difference in the model geometry. Another trajectory result obtained on a stable store (Store 2) is compared with the results obtained from the NEAR method and is shown in Figure 9. Here again the comparison is fairly good except for small differences in pitch and yaw orientations. Further validations and use of the rig for store adaptation studies are currently in progress.

Concluding remarks

A brief description of the various methods used for store separation trajectory is given, along with their relative merits and demerits. The captive trajectory technique, most commonly used in high-speed wind tunnels, is described in some detail. A few examples of the trajectories obtained in the NAL 1.2 m wind tunnel using the CTS rig are discussed.

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